Apparatus And Method For Measurement Of Fields Of Backscattered and Forward Scattered/Reflected Beams By An Object In Interferometry

This application also claims the benefit of U.S. Provisional Application No. 60/460,129, filed April 3, 2003.

Technical Field

This invention relates to the imaging of spots in or on a substrate using interferometry.

Background of the Invention

The prior art teaches the practice of measuring the amplitudes of fields of forward scattered/reflected beams by an object as a function of angle of incidence in ellipsometric measurements. The prior art does not, however, teach backscattered imaging of an object by measuring amplitudes of fields of backscattered beams by an object using either interferometric non-ellipsometric or in interferometric ellipsometric measurements. Nor does it teach backscattered imaging involving joint measurements of conjugated quadratures of fields of backscattered beams by an object using either interferometric non-ellipsometric or in interferometric ellipsometric measurements.

The prior art also teaches the practice of measuring the amplitudes of fields of forward scattered/reflected beams by an object as a function of angle of incidence in ellipsometric measurements for a single spot on a substrate or for a small number of spots on a substrate. It does not, however, teach the practice of backscattered imaging or of measuring the amplitudes of fields of forward scattered/reflected beams by spots in or on a substrate by measuring simultaneously the amplitudes of fields of the backscattered beams or of the forward scattered/reflected beams by an array of a large number of spots in or on an object in either non-interferometric or in interferometric ellipsometric measurements. Nor does it teach the practice of

backscattered imaging or of measuring the amplitudes of fields of forward scattered/reflected beams by spots in or on a substrate with simultaneous joint measurements of conjugated quadratures of fields of the backscattered beams or of the forward scattered/reflected beams by a large array of spots in or on an object in interferometric ellipsometric or non-ellipsometric measurements.

Summary of the Invention

Embodiments of the invention that are described herein generate one-dimensional, two-dimensional, and three-dimensional backscattered images of an object with the measurement of amplitudes of fields of backscattered beams by an object in interferometric non-ellipsometric and in interferometric ellipsometric measurements. Certain embodiments further generate one-dimensional, two-dimensional, and three-dimensional backscattered images of an object with joint measurements of conjugated quadratures of fields of backscattered beams by an object in either interferometric non-ellipsometric or in interferometric ellipsometric measurements.

In other embodiments, backscattered images of an object are generated with simultaneous measurements made of amplitudes of fields of backscattered beams by an array of a large number of spots in or on an object in either interferometric non-ellipsometric or in interferometric ellipsometric measurements. In yet other embodiments, backscattered images of an object are generated with simultaneous measurements made of joint measurements of conjugated quadratures of fields of backscattered beams by a large array of spots in or on an object in either interferometric non-ellipsometric or in interferometric ellipsometric measurements. As will become apparent, many of the embodiments described herein may also be used in forward scattered/reflection imaging of spots in or on a substrate.

In general, in one aspect, the invention features an interferometry system for making interferometric measurements of an object. The system includes a source assembly that generates an input beam; a detector assembly that includes a detector element; and an interferometer that includes a source imaging system that images the input beam onto a spot on or in the object and an object imaging system that

images the spot onto the detector element as an interference beam, wherein the object imaging system combines light coming from the spot with a reference beam to produce the interference beam. The source imaging system is characterized by a first aperture stop that defines a first aperture and includes a first phase shifter that introduces a first phase shift in light passing through a first region of the first aperture relative to light passing through a second region of the first aperture, wherein the second region of the first aperture being the region of the aperture that is outside of the first region of the first aperture. The object imaging system is characterized by a second aperture stop that defines a second aperture and includes a second phase shifter that introduces a second phase shift in light passing through a first region of the second aperture relative to light passing through a second region of the second aperture, wherein the second region of the second aperture being the region of the aperture that is outside of the first region of the second aperture.

Other embodiments include one or more of the following features. The first and second phase shifters are oriented relative to each other such that any component of the input beam that reaches the detector element as a result of being forward scattered/reflected by the object passes through only one of the first and second phase shifters when traversing from the source assembly to the detector element. In addition, the first and second phase shifters are oriented relative to each other such that any component of the input beam that reaches the detector element as a result of being backscattered by the object passes through either both the first and second phase shifters or through neither of the first and second phase shifters when traversing from the source assembly to the detector element. The first phase shift is $\pi/2$ and the second phase shift is $\pi/2$. The first region of the first aperture occupies one half of the area of the first aperture and the first region of the second aperture occupies one half of the area of the second aperture. The first and second regions of the first aperture are of equal area and the first and second regions of the second aperture are of equal area.

Still other embodiments include one or more of the following features. The object imaging system includes a first imaging system, a mask defining a pinhole, and a second imaging system, wherein the first imaging system images the spot on the pinhole of the mask and the second imaging system images the pinhole of the mask onto the detector

element. The second phase shifter is located in the first imaging system. The first imaging system and the source imaging system are both implemented by the same imaging system. The second imaging system images the pinhole onto the detector element. The first phase shifter is a thin optical film on a portion of a surface of an optical element within the source imaging system and the second phase shifter is also implemented by that same thin film. The interferometer includes a catadioptric imaging system that implements both the source imaging system and the first imaging system. The catadioptric imaging system includes a first catadioptric element, a second catadioptric element, and a beam splitter between the first and second catadioptric elements. The source assembly includes a pulsed or shuttered source for generating the input beam. The interferometry system may be an interferometric microscopy system, a interferometric confocal microscopy system, or an interferometric ellipsometric microscopy system, to name only a few possibilities.

In general, in another aspect, the invention features an interferometry system for making interferometric measurements of an object. The system includes: a source assembly that generates an array of input beams; a detector assembly that includes an array of detector elements; and an interferometer that includes a source imaging system that images the array of input beams onto an array of spots on or in the object and an object imaging system that images the array of spots onto the array of detector elements as an array of interference beams, wherein the object imaging system combines light coming from each spot of the array of spots with a corresponding reference beam to produce a corresponding interference beam of the array of interference beams. The source imaging system is characterized by a first aperture stop that defines a first aperture and includes a first phase shifter that introduces a first phase shift in light passing through a first region of the first aperture relative to light passing through a second region of the first aperture, wherein the second region of the first aperture is the region of the aperture that is outside of the first region of the first aperture. The object imaging system is characterized by a second aperture stop that defines a second aperture and includes a second phase shifter that introduces a second phase shift in light passing through a first region of the second aperture relative to light passing through a second region of the

second aperture, wherein the second region of the second aperture being the region of the aperture that is outside of the first region of the second aperture.

Other embodiments include one or more of the following features. The first and second phase shifters are oriented relative to each other such that any component of the array of input beams that reaches the detector element as a result of being forward scattered/reflected by the object passes through only one of the first and second phase shifters when traversing from the source assembly to the detector element. In addition, the first and second phase shifters are oriented relative to each other such that any component of the array of input beams that reaches the detector element as a result of being backscattered by the object passes through either both of the first and second phase shifters or through neither of the first and second phase shifters when traversing from the source assembly to the detector assembly. The object imaging system includes a first imaging system, a object-side mask defining an array of pinholes, and a second imaging system, wherein the first imaging system images the array of spots on the array of pinholes so that each imaged spot of the imaged array of spots is aligned with a corresponding different one of the pinholes of the array of pinholes and wherein the second imaging system images the array of pinholes onto the array of detector elements. The interferometer includes a catadioptric imaging system that implements both the source imaging system and the first imaging system. The catadioptric imaging system includes a first catadioptric element, a second catadioptric element, and a beam splitter between the first and second catadioptric elements. The source assembly includes a source-side mask defining an array of pinholes. The detector-side mask and the source-side mask are implemented by the same mask. The source assembly includes a pulsed source for generating the array of input beams. The interferometry system also includes an object stage for holding the object, a first transducer assembly for moving the object stage so as to scan the object during operation, and a second transducer assembly for moving the detector-side mask during operation. The interferometry system further includes a controller programmed to cause the first transducer to move the object while at the same time causing the second transducer assembly to move the detector-side mask so that the detector-side mask tracks a conjugate image of the substrate during operation.

In general, in still yet another aspect, the invention features a method of making interferometric measurements of an object. The method involves: generating a input beam; deriving first and second measurement beams from the input beam; shifting the first measurement beam in phase relative to the second measurement beam by a first amount; focusing the first and second measurement beams onto a spot on or in the object to produce a first return measurement beam and a second return measurement beam, wherein the first return measurement beam results from forward reflection and/or forward scattering of the first measurement beam by the object plus backscattering of the second measurement beam by the object, and the second measurement beam results from forward reflection and/or forward scattering of the second measurement beam by the object plus backscattering of the first measurement beam by the object; shifting the second return measurement beam in phase relative to the first return measurement beam by a second amount; interfering the first and return second return measurement beams with a reference beam to produce an interference beam; and focusing the interference beam onto the detector element.

Other embodiments include one or more of the following features. The first and second amounts of phase shift are such that the backscattering portions of the first and second return measurement beams substantially cancel and the forward reflected and/or forward scattering portions of the first and second return measurement beams reinforce each other. The first and second amounts of phase shift are equal to $\pi/2$.

An advantage of at least one embodiment is that one-dimensional, two-dimensional, and three-dimensional backscattered images of an object are generated with the measurement of amplitudes of fields of beams backscattered by an object in interferometric non-ellipsometric and in interferometric ellipsometric measurements.

Another advantage of at least one embodiment is that one-dimensional, two-dimensional, and three-dimensional backscattered images of an object are generated with joint measurements of conjugated quadratures of fields of beams backscattered by an object in either interferometric non-ellipsometric or in interferometric ellipsometric measurements.

An advantage of at least one embodiment is that backscattered images of an object are generated with simultaneous measurements of amplitudes of fields of beams backscattered by an array of a large number of spots in or on an object in either interferometric non-ellipsometric or in interferometric ellipsometric measurements.

An advantage of at least one embodiment is that backscattered images of an object are generated with simultaneous measurements of joint measurements of conjugated quadratures of fields of beams backscattered by a large array of spots in or on an object in either interferometric non-ellipsometric or in interferometric ellipsometric measurements.

Another advantage of at least one embodiment is that either bi- or quad-homodyne detection methods can be used in non-ellipsometric measurements to obtain joint measurements of conjugated quadratures of fields of beams reflected/scattered by a substrate being imaged.

Another advantage of at least one embodiment is that either a variant of the bi- or quad-homodyne detection method can be used in ellipsometric measurements to obtain joint measurements of conjugated quadratures of fields of beams reflected/scattered by a substrate being imaged.

Another advantage of at least one embodiment is that relative phase shifts between the arrays of reference and measurement beams can be introduced by changing the frequencies of components of an input beam.

Another advantage of at least one embodiment is backscattered imaging of a substrate with a lateral resolution of the order of microns may be obtained with a working distance of the order of a mm for ellipsometric measurements.

Another advantage of at least one embodiment is backscattered imaging of an interior portion of a substrate with a lateral resolution of the order of microns may be obtained with a working distance of the order of a mm for ellipsometric measurements.

Another advantage of at least one embodiment is that in certain embodiments, the phases of components of an input beam do not affect measured conjugated quadratures of fields.

For each of the advantages with respect to backscattered imaging, there are corresponding advantages with respect to forward scattered/reflection imaging of a substrate.

Brief Description of the Drawings

Fig. 1a is a diagram of an interferometric system that uses the single-, double-, bi-, and quad-homodyne detection methods and variants thereof.

Fig. 1b is a schematic diagram of a confocal microscope system.

Fig. 1c is a schematic diagram of catadioptric imaging system.

Fig. 1d is a schematic diagram of a pinhole array used in a confocal microscope system.

Fig. 1e is a schematic diagram of catadioptric imaging system with a phase shifter.

Detailed Description

Several embodiments are described that comprise interferometric confocal and non-confocal ellipsometric and non-ellipsometric microscopy systems. A general description of embodiments incorporating the present invention will first be given for interferometer systems wherein the single-, double-, bi-, and quad-homodyne detection methods and variants thereof are used for making measurements of conjugated quadratures of fields of either polarized beams or orthogonally polarized beams scattered/reflected by a measurement object. For those embodiments that use bi- and quad-homodyne detection methods and variants thereof, joint measurements are made of conjugated quadratures of fields of either polarized beams or orthogonally polarized beams scattered/reflected by a measurement object.

Referring to Fig. **1a**, an interferometer system is shown diagrammatically comprising an interferometer **10**, a source **18**, a beam-conditioner **22**, detector **70**, an electronic processor and controller **80**, and a measurement object, substrate **60**. Source **18** is a pulsed or shuttered source that generates input beam **20** comprising one or more frequency components. Beam **20** is incident on and exits beam-conditioner **22** as input beam **24** that comprises a single polarized component or two orthogonally polarized

components. Each of the polarized components comprises one or more different frequency components. The measurement beam components of the frequency components of input beam **24** are coextensive in space and have the same temporal window function and the corresponding reference beam components are coextensive in space and have the same temporal window function.

Reference and measurement beams may be generated in either beam-conditioner **22** from a set of beams from source **18** or in interferometer **10** for each of the frequency components of input beam **24**. Measurement beam **30A** generated in either beam-conditioner **22** or in interferometer **10** is incident on substrate **60**. Measurement beam **30B** is a return measurement beam generated as either a portion of measurement beam **30A** reflected and/scattered or transmitted by substrate **60**. Return measurement beam **30B** is combined with the reference beam in interferometer **10** to form output beam **34**.

Output beam **34** is detected by detector **70** to generate one or more electrical interference signals per source pulse for the homodyne detection method used and transmitted as signal **72**. Detector **70** may comprise an analyzer to select common polarization states of the reference and return measurement beam components of beam **34** to form a mixed beam. Alternatively, interferometer **10** may comprise an analyzer to select common polarization states of the reference and return measurement beam components such that beam **34** is a mixed beam.

In the practice, known phase shifts are introduced between the reference and measurement beam components of output beam **34** by two different techniques. In the first technique, phase shifts are introduced between corresponding reference and measurement beam components for each of the frequency components of output beam **34** as a consequence of a non-zero optical path difference between the reference and measurement beam paths in interferometer **10** and corresponding frequency shifts introduced to the frequency components of input beam **24** by beam-conditioner **22** and/or source **18** as controlled by signals **74** and **92**, respectively, from electronic processor and controller **80**. In the second technique, phase shifts are introduced between the reference and measurement beam components for each of the frequency components of input beam **24** by beam-conditioner **22** and/or

source **18** as controlled by signals **74** and **92**, respectively, from electronic processor and controller **80**.

There are different ways to configure source **18** and beam-conditioner **22** to meet the input beam requirements of the different embodiments. Examples of beam-conditioners that may be used in the second technique comprise combinations of a two frequency generator and phase shifting type of beam-conditioner such as described in commonly owned U.S. Provisional Patent Application No. 60/442,858 (47) entitled "Apparatus and Method for Joint Measurements of Conjugated Quadratures of Fields of Reflected/Scattered Beams by an Object in Interferometry" and U.S. Patent Application Serial No. 10/765,369, filed January 27, 2004 (ZI-47) and entitled "Apparatus and Method for Joint Measurements of Conjugated Quadratures of Fields of Reflected/Scattered and Transmitted Beams by an Object in Interferometry". Other examples of beam-conditioners that may be used in the second technique comprising combinations of multiple frequency generators and phase shifting types of beam-conditioners such as described for example in commonly owned U.S. Provisional Patent Application Serial No. 60/459,425 (ZI-50) entitled "Apparatus and Method for Joint Measurement of Fields of Scattered/Reflected Orthogonally Polarized Beams by an Object in Interferometry" and U.S. Patent Application filed April 1, 2004 (ZI-50) also entitled "Apparatus and Method for Joint Measurement of Fields of Scattered/Reflected Orthogonally Polarized Beams by an Object in Interferometry". The two U.S. Provisional Patent Applications and the two U.S. Patent Applications are all by Henry A. Hill and the contents of which are incorporated herein in their entirety by reference.

With a continuation of the description of different ways to configure source **18** and beam-conditioner **22** to meet the input beam requirements of different embodiments, source **18** will preferably comprise a pulsed source. There are a number of different ways for producing a pulsed source [see Chapter 11 entitled "Lasers", *Handbook of Optics,* **1**, 1995 (McGraw-Hill, New York) by W. Silfvast]. Each pulse of source **18** may comprise a single pulse or a train of pulses such as generated by a mode locked Q-switched Nd:YAG laser. A single pulse train is referenced herein as a pulse. The word "pulse" and the phrase "a pulse train" are used herein interchangeably.

Source **18** may be configured in certain embodiments to generate two or more frequencies by techniques such as described in a review article entitled "Tunable, Coherent Sources For High-Resolution VUV and XUV Spectroscopy" by B. P. Stoicheff, J. R.Banic, P. Herman, W. Jamroz, P. E. LaRocque, and R. H. Lipson in *Laser Techniques for Extreme Ultraviolet Spectroscopy*, T.J. McIlrath and R.R. Freeman, Eds., (American Institute of Physics) p 19 (1982) and references therein. The techniques include for example second and third harmonic generation and parametric generation such as described in the articles entitled "Generation of Ultraviolet and Vacuum Ultraviolet Radiation" by S. E. Harris, J. F. Young, A. H. Kung, D. M. Bloom, and G. C. Bjorklund in *Laser Spectroscopy I*, R. G. Brewer and A. Mooradi, Eds. (Plenum Press, New York) p 59, (1974) and "Generation of Tunable Picosecond VUV Radiation" by A. H. Kung, *Appl. Phys. Lett.* **25**, p 653 (1974). The contents of the three cited articles are herein incorporated in their entirety by reference.

The output beams from source **18** comprising two or more frequency components may be combined in beam-conditioner **22** by beam-splitters to form coextensive measurement and reference beams that are either spatially separated or coextensive as required in certain embodiments. The frequency shifting of the various components required in certain embodiments may be introduced in source **18,** for example, by frequency modulation of input beams to parametric generators and the phase shifting of reference beams relative to measurement beams in beam-conditioner **22** may be achieved by phase shifters of the optical-mechanical type comprising for example prisms or mirrors and piezoelectric translators or of the electro-optical modulator type.

The general description is continued with reference to Fig. **1a**. Input beam **24** is incident on interferometer **10** wherein reference beams and measurement beams are generated. The reference beams and measurement beams comprise one or two arrays of reference beams and one or two arrays of measurement beams, respectively, for non-ellipsometric and ellipsometric measurements, respectively, wherein the arrays may comprise arrays of one element. The arrays of measurement beams are focused on and/or in substrate **60** and arrays of return measurement

beams are generated by reflection/scattering by substrate **60**. The arrays of reference beams and return measurement beams are combined by a beam-splitter to form on or two arrays of output beams for non-ellipsometric or ellipsometric measurements, respectively. The arrays of output beams are mixed with respect to state of polarization either in interferometer **10** or in detector **70**. The arrays of output beams are subsequently focused to spots on pixels of a multipixel detector and detected to generate the array of electrical interference signals **72**.

The conjugated quadratures of fields of return measurement beams are obtained by using a single-, double-, bi-, quad-homodyne detection method or variant thereof. The bi- and quad-homodyne detection methods are described for example in cited U.S. Provisional Patent Application No. 60/442,858 (47) and U.S. Patent Application Serial No. 10/765,369, filed January 27, 2004 (ZI-47) and entitled "Apparatus and Method for Joint Measurements of Conjugated Quadratures of Fields of Reflected/Scattered and Transmitted Beams by an Object in Interferometry". The variants of the bi- and quad-homodyne detection methods are described for example in cited U.S. Provisional Patent Application No. 60/459,425 (ZI-50) and U.S. Patent Application filed April 1, 2004 (ZI-50) and entitled "Apparatus and Method for Joint Measurement of Fields of Scattered/Reflected Orthogonally Polarized Beams by an Object in Interferometry".

For the single-homodyne detection method, input beam **24** comprises a single frequency component and sets of four or eight measurements of the array of electrical interference signals **72** is made in non-ellipsometric or ellipsometric measurements, respectively. For each of the measurements of the array of electrical interference signals **72** in non-ellipsometric and ellipsometric measurements, known phase shifts are introduced between each reference beam component and respective return measurement beam component of output beam **34**. The subsequent data processing procedure used to extract the conjugated quadratures of fields of beams reflected and/or scattered by a substrate is described for example in commonly owned U.S. Patent No. 6,445,453 (ZI-14) entitled "Scanning Interferometric Near-Field Confocal Microscopy" by Henry A. Hill, the contents of which are incorporated herein in their entirety by reference.

The double-homodyne detection method which is applicable to non-ellipsometric measurements uses input beam **24** comprising four frequency components and four detectors to obtain measurements of electrical interference signals that are subsequently used to obtain conjugated quadratures in non-ellipsometric measurements. Each detector element of the four detector elements obtains a different one of the four electrical interference signal values with the four electrical interference signal values obtained simultaneously to compute the conjugated quadratures for a field. Each of the four electrical interference signal values contains only information relevant to one orthogonal component of the conjugated quadratures. The double-homodyne detection used herein is related to the detection methods such as described in Section IV of the article by G. M D'ariano and M G. A. Paris entitled "Lower Bounds On Phase Sensitivity In Ideal And Feasible Measurements," *Phys. Rev. A* 49, 3022-3036 (1994). Accordingly, the double- homodyne detection method does not make joint determinations of conjugated quadratures of fields wherein each electrical interference signal value contains information simultaneously about each of two orthogonal components of the conjugated quadratures.

In the adaptation of the double-homodyne detection method to ellipsometric measurements, input beam **24** comprises eight frequency components and eight detectors to obtain measurements of eight electrical interference signals that are subsequently used to obtain conjugated quadratures. Each detector element of the eight detector elements obtains a different one of the eight electrical interference signal values with the eight electrical interference signal values obtained simultaneously to compute the conjugated quadratures of fields of scattered/reflected orthogonally polarized fields. Each of the eight electrical interference signal values contains only information relevant to one orthogonal component of one of the two conjugated quadratures.

The bi- and quad-homodyne detection methods obtain measurements of electrical interference signals wherein each measured value of an electrical interference signal contains simultaneously information about two orthogonal components of conjugated quadratures. The two orthogonal components correspond

to orthogonal components of conjugated quadratures such as described in cited U.S Provisional Patent Application No. 60/442,858 (ZI-47) and cited U.S. Patent Application Serial No. 10/765,369, filed January 27, 2004 (ZI-47) entitled "Apparatus and Method for Joint Measurements of Conjugated Quadratures of Fields of Reflected/Scattered and Transmitted Beams by an Object in Interferometry".

The variants of the bi- and quad-homodyne detection methods obtain measurements of electrical interference signals wherein each measured value of an electrical interference signal contains simultaneously information about two orthogonal components of each of two conjugated quadratures of fields of scattered/reflected orthogonally polarized beams. The two orthogonal components of the two conjugated quadratures correspond to orthogonal components of conjugated quadratures such as described in cited U.S Provisional Patent Application No. 60/459,425 (ZI-50) and cited U.S. Patent Application filed April 1, 2004 (ZI-50) and entitled “Apparatus and Method for Joint Measurement of Fields of Scattered/Reflected Orthogonally Polarized Beams by an Object in Interferometry”.

A first embodiment is shown schematically in Fig. **1b**. The first embodiment comprises a first imaging system generally indicated as numeral **10**, pinhole array beam-splitter **12**, detector **70**, and a second imaging system generally indicated as numeral **110**. The second imaging system **110** is low power microscope having a large working distance, *e.g.* Nikon ELWD and SLWD objectives and Olympus LWD, ULWD, and ELWD objectives.

The first imaging system **10** is shown schematically in Fig. **1c**. The imaging system **10** is a catadioptric system such as described in commonly owned U.S. Patent Application No. 10/028,508 (ZI-38) and U.S. Patent No. 6,717,736 (ZI-43) both of which are entitled "Catoptric and Catadioptric Imaging System." Both of the two cited patent applications are by Henry A. Hill and the contents of the two cited patent applications are incorporated herein in their entirety by reference.

Catadioptric imaging system **10** comprises catadioptric elements **40** and **44**, beam-splitter **48**, and convex lens **50**. Surfaces **42A** and **46A** are convex spherical

surfaces with nominally the same radii of curvature and the respective centers of curvature of surfaces **42A** and **46A** are conjugate points with respect to beam-splitter **48**. Surfaces **42B** and **46B** are concave spherical surfaces with nominally the same radii of curvature. The centers of curvature of surfaces **42B** and **46B** are the same as the centers of curvature of surfaces **46A** and **42A**, respectively. The center of curvature of convex lens **50** is the same as the center of curvature of surfaces **42B** and **46A**. The radius of curvature of surface **46B** is selected so as to minimize the loss in efficiency of the imaging system **10** and to produce a working distance for imaging system **10** acceptable for an end use application. The radius of curvature of convex lens **50** is selected so that the off-axis aberrations of the catadioptric imaging system **10** are compensated. The medium of elements **40** and **44** may be for example CaF_2, fused silica or commercially available glass such as SF11. The medium of convex lens **50** may be for example CaF_2, fused silica, YAG, or commercially available glass such as SF11. An important consideration in the selection of the medium of elements **40** and **44** and convex lens **50** will the transmission properties for the frequencies of beam **24**.

Convex lens **52** has a center of curvature the same as the center of curvature of convex lens **50**. Convex lenses **50** and **52** are bonded together with pinhole beam-splitter **12** in between. Pinhole array beam-splitter **12** is shown in Fig. **1d**. The pattern of pinholes in pinhole array beam-splitter is chosen to match the requirements of an end use application. An example of a pattern is a two dimensional array of equally spaced pinholes in two orthogonal directions. The pinholes may comprise circular apertures, rectangular apertures, or combinations thereof such as described in commonly owned U.S. Patent Application No. 09/917,402 (ZI-15) entitled "Multiple-Source Arrays for Confocal and Near-field Microscopy" by Henry A. Hill and Kyle Ferrio of which the contents thereof are incorporated herein in their entirety by reference. The pinholes may also comprise microgratings such as described in cited U.S. Provisional Patent Application No. 60/459,425 (ZI-50) and U.S. Patent Application filed April 1, 2004 (ZI-50) and entitled "Joint Measurement Of Fields Of Orthogonally Polarized Beams Scattered/Reflected By An Object In Interferometry".. A nonlimiting example of a

pinhole array for pinhole array beam-splitter **12** is shown in Fig. **1d** having a spacing between pinholes of b with aperture size a.

The description of the imaging properties of catadioptric imaging system **10** is the same as the corresponding portion of the description given for the imaging properties of catadioptric imaging system **10** in commonly owned U.S. Provisional Patent Application No. 60/442,982 (ZI-45) entitled "Interferometric Confocal Microscopy Incorporating Pinhole Array Beam-Splitter" and U.S. Patent Application No. 10/765,229, filed January 27, 2004 (ZI-45) and also entitled "Interferometric Confocal Microscopy Incorporating Pinhole Array Beam-Splitter" both of which are by Henry A. Hill. The contents of both of the U.S. Provisional Patent Application and the U.S. Patent Application are herein incorporated in their entirety by reference.

Input beam **24** is reflected by mirror **54** to pinhole beam-splitter **12** where a first portion thereof is transmitted as reference beam components of output beam components **32A** and **32B** (see Fig. **1b**) and a second portion thereof scattered as measurement beam components of beam components **26A** and **26B**. The measurement beam components of beam components **26A** and **26B** are imaged as components of beam components **28A** and **28B** to an array of image spots in an image plane close to the surface of substrate **60**. A portion of the components of beam components **28A** and **28B** incident on substrate **60** are reflected and/or scattered as return measurement beam components of beam components **28A** and **28B**. Return measurement beam components of beam components **28A** and **28B** are imaged by catadioptric imaging system **10** to spots that are coincident with the pinholes of pinhole beam-splitter **12** and a portion thereof is transmitted as return measurement beam components of output beam components **32A** and **32B**.

The next step is the imaging of output beam components **32A** and **32B** by imaging system **110** to an array of spots that coincide with the pixels of a multi-pixel detector such as a CCD to generate an array of electrical interference signals **72**. The array of electrical interference signals is transmitted to signal processor and controller **80** for subsequent processing.

Conjugated quadratures of fields of the return measurement beam are obtained in embodiments by one of the single-, double-, bi-, and quad-homodyne detection methods and variants thereof. For the homodyne detection methods, a set

of measurements of electrical interference signals **72** is made. For each of the sets of measurements of the electrical interference signals **72**, known phase shifts are introduced between the reference beam components and respective return measurement beam components of output beam components **32A** and **32B**. A non-limiting example of a known set of phase shifts for the single-homodyne detection method comprise 0, $\pi/4$, $\pi/2$, and $3\pi/2$ radians, mod 2π.

In practice, the known phase shifts introduced between the reference beam components and respective measurement beam components of output beam components **32A** and **32B** are generated by two different techniques. In one technique, phase shifts are introduced between the reference beam components and the respective measurement beam components for each of the frequency components of beam **24** by source **18** and beam-conditioner **22** as controlled by signals **92** and **74**, respectively, from electronic processor and controller **80**. In the second technique, phase shifts are introduced between the reference and measurement beam components for each of the frequency components as a consequence of frequency shifts introduced to the frequency components of input beam **24** by source **18** and beam-conditioner **22** as controlled by signals **92** and **74**, respectively, from electronic processor and controller **80**.

With respect to the second technique, an optical path difference L is introduced between the reference beam components and the respective return measurement beam components of output beam components **32A** and **32B**. As a consequence, there will be for a frequency shift Δf a corresponding phase shift φ where

$$\varphi = 2\pi L\left(\frac{\Delta f}{c}\right) \tag{1}$$

and c is the free space speed of light. Note that L is not a physical path length difference and depends for example on the average index of refraction of the measurement beam and the return measurement beam paths. For an example of a

phase shift $\varphi = \pi, 3\pi, 5\pi, \ldots$ and a value of $L = 0.25$ m, the corresponding frequency shift $\Delta f = 600$ MHz, 1.8 GHz, 3.0 GHz, … .

Two different modes of operation are described for the acquisition of the four or eight electrical interference signal values. The first mode to be described is a step and stare mode wherein substrate **60** is stepped between fixed locations for which image information is desired. The second mode is a scanning mode. In the step and stare mode for generating a one-, a two-, or a three-dimensional image of substrate **60**, substrate **60** is translated by stage **90** wherein substrate **60** is mounted on wafer chuck **84** with wafer chuck **84** mounted on stage **90**. The position of stage **90** is controlled by transducer **82** according to servo control signal **78** from electronic processor and controller **80**. The position of stage **90** is measured by metrology system **88** and position information acquired by metrology system **88** is transmitted to electronic processor and controller **80** to generate an error signal for use in the position control of stage **90**. Metrology system **88** may comprise for example linear displacement and angular displacement interferometers and cap gauges.

Electronic processor and controller **80** translates stage **90** to a desired position and then acquires the set of four or eight electrical interference signal values. After the acquisition of the sequence of four or eight electrical interference signal values, electronic processor and controller **80** then repeats the procedure for the next desired position of stage **90**. The elevation and angular orientation of substrate **60** is controlled by transducers **86A** and **86B**.

The second of the two modes for the acquisition of the electrical interference signal values is next described wherein the electrical interference signal values are obtained with the position of stage **90** scanned in one or more directions. In the scanning mode, source **18** is pulsed at times controlled by signal **92** from signal processor and controller **80**. Source **18** is pulsed at times corresponding to the registration of the conjugate image of pinholes of pinhole array beam-splitter **12** with positions on and/or in substrate **60** for which image information is desired.

There will be a restriction on the duration or "pulse width" of a beam pulse τ_{p1} produced by source **18** as a result of the continuous scanning used in the scanning mode of the first embodiment unless pinhole array **12** is scanned to track the conjugate image of substrate **60** at pinhole array **12** such as described in cited U.S. Provisional Patent Application No. 60/442,982 (ZI-45) and U.S. Patent Application No. 10/765,229, filed January 27, 2004 (ZI-45) and entitled "Interferometric Confocal Microscopy Incorporating Pinhole Array Beam-Splitter". Pulse width τ_{p1} will be a parameter that in part controls the limiting value for spatial resolution in the direction of a scan to a lower bound of

$$\tau_{p1}V \text{ ,} \tag{2}$$

where V the scan speed. For example, with a value of $\tau_{p1} = 50$ nsec and a scan speed of $V = 0.20$ m/sec, the limiting value of the spatial resolution $\tau_{p1}V$ in the direction of scan will be

$$\tau_{p1}V = 10 \text{ nm} . \tag{3}$$

Pulse width τ_{p1} will also determine the minimum frequency difference that can be used in the bi- and quad-homodyne detection methods and variants thereof. In order that no contributions to the electrical interference signals are generated from interference between fields of conjugated quadratures, the minimum frequency spacing $\Delta f_{\min}$ is expressed as

$$\Delta f_{\min} \gg \frac{1}{\tau_{p1}} . \tag{4}$$

For an example of $\tau_{p1} = 50$ nsec, $1/\tau_{p1} = 20$ MHz.

In the first mode, *i.e.*, the step and stare mode, each set of the sets of arrays of electrical interference signal values corresponding to the set of phase shift values are generated by a single pixel of detector **70** for single- and bi-homodyne detection methods and variants thereof, by two pixels of detector **70** for the quad-homodyne detection method and variant thereof, by four pixels of detector **70** for the double-homodyne detection method, and by eight pixels of detector **70** for the variant of the double-homodyne detection method. In the second mode for the acquisition of the electrical interference signal values, each corresponding set of electrical interference signal values are generated by a conjugate set of different pixels of detector **70** for each of the four homodyne detection methods and variants thereof. Thus in the first mode of acquisition, the differences in pixel efficiency are compensated in the signal processing by signal processor and controller **80** for the double-, bi-, and quad-homodyne detection methods and in variants of the bi- and quad-homodyne detection methods. In the second mode of acquisition, the differences in pixel efficiency and the differences in sizes of pinholes in pinhole array beam-splitter **12** need to be compensated in the signal processing by electronic processor and controller **80** to obtain conjugated quadratures of fields of return measurement beam components.

The advantage of the second mode is that the electrical interference signal values are acquired in a scanning mode which increases throughput of the interferometric confocal and non-confocal microscopy systems.

The processing of the measured arrays of sets of measured electrical interference signal values for the determination of conjugated quadratures of fields of return measurement beams is described in cited references. With respect to the bi- and quad-homodyne detection methods wherein conjugated quadratures are obtained jointly, a set of four electrical interference signal values is obtained for each spot on and/or in substrate **60** being imaged. The processing of the measured arrays of sets of measured electrical interference signal values for the determination of conjugated quadratures of fields of return measurement beams is described for example in cited U.S. Provisional Patent Application No. 60/442,858 (ZI-47) and cited U.S. Patent Application Serial No. 10/765,369, filed January 27, 2004 (ZI-47)

and entitled "Apparatus and Method for Joint Measurements of Conjugated Quadratures of Fields of Reflected/Scattered and Transmitted Beams by an Object in Interferometry.".

With respect to the variants of the bi- and quad-homodyne detection methods wherein conjugated quadratures are obtained jointly, a set of eight electrical interference signal values is obtained for each spot on and/or in substrate **60** being imaged. The processing of the measured arrays of sets of measured electrical interference signal values for the determination of conjugated quadratures of fields of return measurement beams is described for example in cited U.S. Provisional Patent Application No. 60/459,425, filed April 1, 2003 (ZI-50) and cited U.S. Patent Application filed April 1, 2004 (ZI-50) and entitled " Apparatus and Method for Joint Measurement of Fields of Scattered/Reflected Orthogonally Polarized Beams by an Object in Interferometry", both of which are incorporated herein by reference.

In the embodiment, multi-pixel detector **70** may comprise a frame transfer CCD that is configured such that one set of CCD pixel signal values may be generated and subsequently stored on the CCD wafer while a frame of a second set of CCD pixel signal values may be generated before a readout of both the first and second set of the CCD signal values is made. The time required to store the first set of CCD signal values is generally much less than the time required to readout a set of CCD signal values for a frame transfer CCD. Thus, the advantage of the use of a frame transfer CCD is that the time between two consecutive pulses of input beam **20** and the corresponding time between measurements of electrical interference signal values can be much less than when using a non-frame transfer CCD.

The first embodiment is configured for non-ellipsometric non-joint measurement of conjugated quadratures of fields of beams scattered/reflected at the spots in or on substrate **60**. In the first embodiment, input beam **24** comprises one frequency component wherein non-joint measurements of conjugated quadratures are obtained using the single homodyne detection method. The phase shifts between the reference beam components and the respective return beam components of output beam components **32A** and **32B** are generated in the first embodiment by shifting the frequency of the input beam **24** between known frequency values.

There is a difference in optical path length between the reference beam components and the respective return beam components of output beam components **32A** and **32B** and as a consequence, a change in frequency of input beam **24** will generate a corresponding phase shift between the reference beam components and the respective return beam components of output beam components **32A** and **32B**.

A second embodiment is described that is configured for non-ellipsometric joint measurement of conjugated quadratures of fields of beams scattered/reflected at the spots in or on substrate **60**. The second embodiment comprises the interferometric confocal microscopy system of the first embodiment operated for joint measurement of conjugated quadratures using the bi-homodyne detection method. In the second embodiment, beam-conditioner **22** is operated to generate beam **24** comprising two frequency-shifted components.

The remaining description of the second embodiment is the same as corresponding portions of the description given of the first embodiment.

The sum of the forward scattered/reflected components and the backscattered components of return measurement beam components of beam components **26A** and **26B** are measured in the first or second embodiments by making a first non-joint or joint measurement, respectively, of the conjugated quadratures of fields of measurement beams scattered/reflected at the spots in or on substrate **60** as described. Next a $\pi/2$ phase shifter is introduced either at concave surface **42B** or at concave surface **46B** for either the right half or left half of the aperture of the imaging system **10** shown in Fig. **1c**. An example of a $\pi/2$ phase shifter **46C** is shown in Fig. **1e** in the right half of the aperture of imaging system **10** at concave surface **46B**. With $\pi/2$ phase shifter **46C** in place, the forward scattered/reflected components and the backscattered components of return measurement beam components of beams **26A** and **26B** are next measured in the first or second embodiments, respectively, by making a second non-joint or joint measurement, respectively, of the conjugated quadratures of fields of measurement beams scattered/reflected at the spots in or on substrate **60**.

The relative phase of the reference and return measurement beam components of beams **32A** and **32B** are the same in both of the first and second set

of non-joint or joint measurements of the conjugated quadratures of fields of measurement beams scattered/reflected at the spots in or on substrate **60** for the forward scattered/reflected components. However, as a consequence of the $\pi/2$ phase shift introduced by the $\pi/2$ phase shifter **46C**, the relative phase of the backscattered components of return measurement beam components of beams **32A** and **32B** are different by π and as a result interferometrically cancel out in the second set of non-joint or joint measurements, respectively, of the conjugated quadratures of fields of measurement beams scattered/reflected at the spots in or on substrate **60**. As a consequence of the effect of $\pi/2$ phase shifter **46C**, only the forward scattered/reflected component of the fields scattered/reflected by the spots on or in substrate **60** is obtained from the second set of non-joint or joint measurements, respectively, of the conjugated quadratures of fields. Accordingly the backscattered component of the fields scattered/reflected by the spots on or in substrate **60** is obtained by subtracting the second set of non-joint or joint measurements, respectively, of the conjugated quadratures of fields from the first set of non-joint or joint measurements, respectively, of the conjugated quadratures of fields.

The measurement of the backscattered component of the fields scattered/reflected by the spots on or in substrate **60** permits for example the measurement of critical dimensions of arrays of trenches with sub-wavelength trench widths. Also the number of trenches in an array of trenches that have a total width less than the lateral resolution of imaging system **10** can be determined. The backscattering measurement feature is particularly valuable in the measurement of properties of trenches because of the constructive interference properties of the backscattered fields from an array of trenches functioning as a grating of a finite number of rulings.

A third embodiment is described that comprises the interferometric confocal microscopy system of the first embodiment operated for joint measurement of conjugated quadratures of fields of beams scattered/reflected at the spots in or on substrate **60** using the quad-homodyne detection method. In the third embodiment, source **18** and beam-conditioner **22** are operated to generate beam **24** comprising

four frequency-shifted components. The remaining description of the third embodiment is the same as corresponding portions of the description given of the first embodiment.

A fourth embodiment is described that comprises the interferometric confocal microscopy system of the first embodiment operated for non-joint measurement of conjugated quadratures of fields of beams scattered/reflected at the spots in or on substrate **60** using the double-homodyne detection method. In the fourth embodiment, source **18** and beam-conditioner **22** are operated to generate beam **24** comprising four frequency-shifted components. The remaining description of the fourth embodiment is the same as corresponding portions of the description given of the first embodiment.

In other embodiments, the first, second, third, and fourth embodiments are configured to make ellipsometric non-joint and joint measurements of fields of scattered/reflected orthogonally polarized beams by the spots on or in substrate **60**. The first, second, third, and fourth embodiments use variants of the single-, double-, bi-, and quad-homodyne detection methods such as described in cited U.S. Provisional Patent Application No. 60/459,425 (ZI-50] and U.S. Patent Application filed April 1, 2004 (ZI-50) entitled "Apparatus and Method for Joint Measurement Of Fields Of Scattered/Reflected Orthogonally Polarized Beams By An Object In Interferometry". In the other embodiments, pinhole array **12** may be replaced by an array of microgratings such as described in cited U.S. Provisional Patent Application No. 60/459,425 (ZI-50] and U.S. Patent Application filed April 1, 2004 (ZI-50) entitled "Apparatus and Method for Joint Measurement Of Fields Of Scattered/Reflected Orthogonally Polarized Beams By An Object In Interferometry".

The information obtained in the other embodiments are of the ellipsometric type and furnish additional information with respect to the behavior of the backscattered fields with respect to state of polarization of the measurement beam at the spot in or on substrate **60**.

In embodiments, pinhole array beam-splitter **12** may be scanned in a direction opposite to the direction of scan of substrate **60** and with a speed such that

the conjugate images of the pinholes of pinhole array beam-splitter **12** stay superimposed with spots on or in substrate **60** that are being imaged. This scanning mode of operation reduces the restriction on the pulse width τ_{p1} and is analogous to the relative motions of reticle stage and a wafer stage of a lithography tool operating in a scanning mode. The issue of traditional critical alignment of conjugate confocal pinholes in a confocal microscopy system is non-exsistent, *i.e.* the registration of the pinholes generating the array of reference beams and the pinholes generating the array of measurement beams is automatic.

In certain end use applications, the interior of substrate **60** is imaged. In this case, there will be aberrations introduced. In another embodiment, compensation for aberrations is accomplished by introducing a thin layer (the thin layer has an index of refraction different from lens **50**) between lens **50** and pinhole array beam-splitter **12** such as described in commonly owned U.S. Provisional Application No. 60/444,707 (ZI-44) entitled "Compensation of Effects of Mismatch in Indices of Refraction At a Substrate-Medium Interface in Confocal and Interferometric Confocal Microscopy" and U.S. Patent Application No. 10/771,785, filed February 4, 2004 (ZI-44) and also entitled "Compensation for Effects of Mismatch in Indices of Refraction at a Substrate-Medium Interface in Confocal and Interferometric Confocal Microscopy" both of which are by Henry A. Hill. The contents of the U.S. Provisional Patent Application and the U.S. Patent Application are incorporated herein in their entirety by reference.

For certain other embodiments, phase shifts are introduced in interferometer **10** of Fig. **1a** that serve the function of the $\pi/2$ phase shifter **46C** of the cited embodiments, *i.e.*, the first, second, third, and fourth embodiments and other embodiments. In each of the certain other embodiments, there is an imaging system for imaging substrate **60** onto a pinhole array and/or multi-pixel detector array and an imaging system for imaging a source onto substrate **60**. These two imaging systems may comprise the same imaging system such as for the cited embodiments. In the certain other embodiments, the two imaging systems may be two independent imaging systems or have common portions thereof. In each embodiment of the certain embodiments, the function of the $\pi/2$ phase shifter **46C** of the cited

embodiments, wherein the two imaging systems are the same, is achieved in interferometer **10** of Fig. **1a** by the introduction of a $\pi/2$ phase shifter in one half of the aperture of the stop for each of the two imaging systems. (Note: In general, an imaging system is characterized by an aperture stop that defines an aperture or opening through which the light that forms the image will pass. That is, the aperture stop limits the cross-section of light that will form the image.) The relative orientations of the two phase shifters are such that any component of a measurement beam that reaches the detector as a component that is forward scattered/reflected by substrate **60** will a pass through either one of the two $\pi/2$ phase shifters, but not both as it traverses from the source to the detector. On the other hand, any component of a measurement beam that reaches the detector as a component that is backscattered by substrate **60** will either pass through both phase shifters or neither phase shifter as it traverses from the source to the detector. In the cases where the two imaging systems share a common portions thereof, the role of the two $\pi/2$ phase shifters that cover one half of the apertures of the stops for each of the two imaging systems may be achieved by a single $\pi/2$ phase shifter, such as in the case of the cited embodiments.

A fifth embodiment comprises the interferometer system of Fig. **1a** with interferometer **10** comprising an interferometric far-field confocal microscope such as described in commonly owned U.S. Patent No. 5,760,901 entitled "Method And Apparatus For Confocal Interference Microscopy With Background Amplitude Reduction and Compensation" by Henry A. Hill, the contents of which are herein incorporated in their entirety by reference. In the fifth embodiment, source **18** and beam-conditioner **22** are configured to operate in a phase shifting mode. The fifth embodiment has reduced effects of background because of background reduction features of cited U.S. Patent No. 5,760,901.

A sixth embodiment comprises the interferometer system of Fig. **1a** with interferometer **10** comprising an interferometric far-field confocal microscope such as described in cited U.S. Patent No. 5,760,901 wherein the phase masks are removed. In the sixth embodiment, source **18** and beam-conditioner **22** are configured to operate in a phase shifting mode. The sixth embodiment with the

phase masks of embodiments of cited U.S. Patent No. 5,760,901 removed represent applications of confocal techniques in a basic form.

A seventh embodiment comprises the interferometer system of Fig. **1a** with interferometer **10** comprising an interferometric far-field confocal microscope such as described in commonly owned U.S. Patent No. 6,480,285 B1 entitled "Multiple Layer Confocal Interference Microscopy Using Wavenumber Domain Reflectometry and Background Amplitude Reduction and Compensation" by Henry A. Hill, the contents of which are herein incorporated in their entirety by reference. In the seventh embodiment, source **18** and beam-conditioner **22** are configured to operate in a phase shifting mode. The seventh embodiment has reduced effects of background because of background reduction features of cited U.S. Patent No. 6,480,285 B1.

An eighth embodiment comprises the interferometer system of Fig. **1a** with interferometer **10** comprising an interferometric far-field confocal microscope such as described in cited U.S. Patent No. 6,480,285 B1 wherein the phase masks are removed. In the eighth embodiment, source **18** and beam-conditioner **22** are configured to operate in a phase shifting mode. The eighth embodiment with the phase masks of embodiments of cited U.S. Patent No. 6,480,285 B1 removed represent applications of confocal techniques in a basic form.

A ninth embodiment comprises the interferometer system of Fig. **1a** with interferometer **10** comprising an interferometric near-field confocal microscope such as described in commonly owned U.S. Patent No. 6,445,453 (ZI-14) entitled "Scanning Interferometric Near-Field Confocal Microscopy" by Henry A. Hill, the contents of which are herein incorporated in their entirety by reference. In the ninth embodiment, source **18** and beam-conditioner **22** are configured to operate in a phase shifting mode. The eighth embodiment of cited U.S. Patent No. 6,445,453 in particular is configured to operate in a mode with the measurement beam separated from the reference beam and incident on the substrate being imaged by a non-confocal imaging system, *i.e.*, the measurement beam at the substrate is not an image of an array of pinholes but an extended spot. Accordingly, the corresponding

embodiments of the ninth embodiment represent a non-confocal configuration for the measurement beam in both non-ellipsometric and ellipsometric measurements.

1 Other embodiments are within the following claims.